Dialkylphosphinoimidazoles as New Ligands for Palladium-Catalyzed Coupling Reactions of Aryl Chlorides

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Abstract: *N*-Aryl-2-(dialkylphosphino)imidazoles and -benzimidazoles are conveniently prepared in one step from the corresponding heterocycles by selective deprotonation and quenching with chlorophosphines. The novel ligands are easily tunable and show good to excellent performance in palladium-catalyzed Suzuki reactions and Buchwald–Hartwig aminations of aryl and heteroaryl chlorides.

Keywords: amination; aryl chlorides; homogeneous catalysis; palladium; phosphines; Suzuki reaction

Introduction

Palladium-catalyzed coupling reactions of aryl halides offer numerous interesting possibilities for fine chemicals synthesis.[1] Based on methodological developments achieved by a number of academic (and industrial) groups since the early 1970s various industrial processes, which are based on this chemistry, have been introduced. The rapid increase both on laboratory but also industrial scale is seen by the fact that at the end of the 1980s only one or two refinement reactions of aryl halides have been commercialized, while nowadays more than 20 processes have been used or are applied in industry.[2] The main advantages of these coupling processes compared to classic aromatic functionalization reactions are the ready availability of the starting materials, the generality of the methods and the broad tolerance of the palladium catalysts with various functional groups.

In order to apply more and more of these reactions in the fine chemical industry further significant cost reductions of the generally developed laboratory-scale syntheses must still occur. Efforts to substitute costly starting materials such as aryl iodides or triflates by economically more attractive chloroarenes, reduction of catalyst concentration, etc. are to be seen in this respect. Another important factor for further application of palladium-catalyzed coupling reactions is the development of more efficient and economically attractive catalysts. There exists still a clear need for cheap available ligands which lead to highly active catalyst systems, which are easily tunable and allow for easy scale-up.

Here, we report the synthesis and application of novel phosphine ligands, *N*-aryl-2-(dialkylphosphino)imidazoles, which fulfill these criteria. Various *N*-aryl-2-(dialkylphosphino)imidazoles (Figure 1) can be synthesized in only 1 or 2 reaction steps on multi-g to kg scales. All of the prepared ligands show good to excellent catalyst performance in two widely-used palladium-catalyzed coupling reactions, the Suzuki and Buchwald–Hartwig amination reactions.

Due to the importance of biaryls and aromatic amines as intermediates for the synthesis of pharmaceuticals, agrochemicals and new materials, we have chosen cross-coupling reactions of aryl halides with arylboronic acids (Suzuki reaction)[3] and primary or secondary amines (Buchwald–Hartwig amination)[4] as test reactions of our ligands. Clearly, these methods have been significantly improved in the last decade and have been intensively studied and applied in organic synthesis.

Although even metal-free Suzuki reactions of aryl bromides and iodides are known,[5] less reactive, but commercially attractive, chloroarenes cannot be cou-

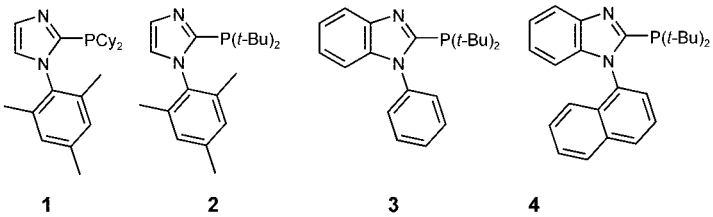

Figure 1. *N*-Aryl-2-(dialkylphosphino)imidazoles

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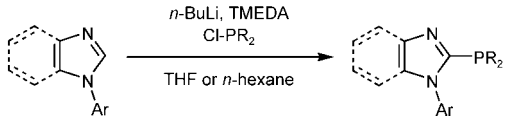
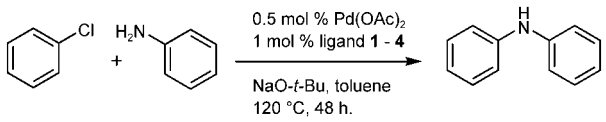


Scheme 1. General synthesis of *N*-aryl-2-(dialkylphosphino)-imidazoles and *N*-aryl-2-(dialkylphosphino)benzimidazoles.



Scheme 2. Palladium-catalyzed reaction of chlorobenzene and aniline.

pled under these conditions. Notable recent catalyst developments for the use of aryl chlorides[6] have been reported by Bedford,[7] Buchwald,[8] Fu,[9] Herrmann,[10] Nolan,[11] us,[12] and others.[13] In addition, our group has reported the use of di-(1-adamantyl)-*n*-butylphosphine[12c,14] and *N*-aryl-2-(dialkylphosphino)pyrrole/indole as highly active ligands for the coupling of a wide range of aryl chlorides with phenylboronic acid[12a] and amines,[15] respectively. Nevertheless, there is a continuous interest in efficient but more practical new ligands.

Results and Discussion

By virtue of the most acidic proton at the C-2 position in the imidazole ring and similar to our previous report on *N*-aryl-2-(dialkylphosphino)pyrroles/indoles,[12a,15] we synthesized the four different *N*-aryl-2-(dialkylphosphino)imidazoles/benzimidazoles depicted in Figure 1.[16] *N*-Mesityl-1*H*-imidazole was prepared by condensation of mesitylamine, paraformaldehyde, glyoxal and ammonium chloride[17] while *N*-arylbenzimidazoles were prepared by copper-catalyzed *N*-arylation of benzimidazole.[18] The obtained *N*-arylated (benz)imidazoles were then deprotonated by a mixture of *n*-BuLi (1.0 equiv.) and TMEDA (1.06 equivs.) in *n*-hexane or THF. *N*-Mesityl-1*H*-imidazole was easily deprotonated at room temperature, whereas *N*-phenyl-1*H*-benzimidazole and *N*-naphthyl-1*H*-benzimidazole required careful deprotonation at a lower reaction temperature ($-65\,^{\circ}C$). The resulting carbanions were subsequently reacted with the corresponding dialkylchlorophosphines giving the desired phosphines in moderate to good yields: 58% **1**, 80% **2**, 41% **3**, and 33% **4** (Scheme 1).

Amination Reactions (Buchwald–Hartwig Amination)

Initially, the reaction of chlorobenzene with aniline was chosen to test the new ligands **1**–**4** (Scheme 2, Table 1). With the dicyclohexylphosphino-substituted ligand **1** diphenylamine was obtained in good yield (87%; Table 1, entry 1), while the di-*tert*-butylphosphino-substituted imidazole and benzimidazole ligands **2**–**4** gave even better yields of 92–99% (Table 1, entries 2–5). Entry 3 shows that the reaction is finished after 8 h (99% yield) which corresponds to a TON of *ca.* 200. The somewhat lower productivity of ligand **1** compared to ligands **2**–**4** is probably due to the decreased steric bulk of the cyclohexyl groups.

Table 1. Amination of chlorobenzene with aniline using ligands **1**–**4**.

Entry	Ligand	Conversion [%][a]	Yield [%][a]	TON[a]
1	**1**	88	87	174
2	**2**	100	99	198
3[b]	**2**	100	99	198
4	**3**	92	92	182
5	**4**	100	99	198

Reaction conditions: 5 mmol chlorobenzene, 6 mmol aniline, 6 mmol NaO-*t*-Bu, 0.5 mol % $Pd(OAc)_2$, 1 mol % ligand, 5 mL toluene, 48 h, 120 °C. Reaction time has not been minimized.

[a] Average of two runs, determined by GC using diethylene glycol di-*n*-butyl ether as internal standard.

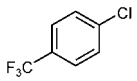
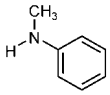
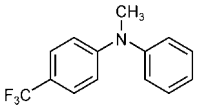
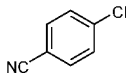
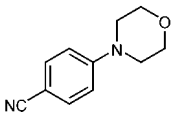
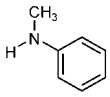
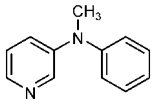
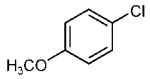
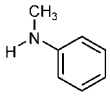
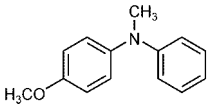
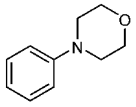
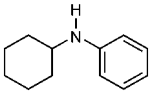
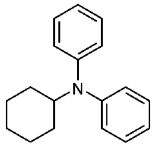
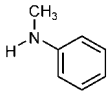
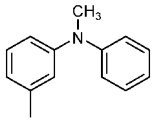
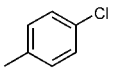
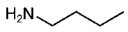
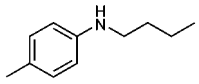
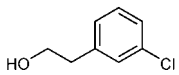
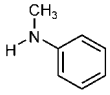
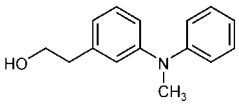
[b] 8 h.

Table 2 emphasizes the general usefulness of this new catalyst system. Applying ligands **2** and **4** in almost all cases the coupling product was obtained in good to excellent yield in the presence of 0.5 mol % Pd. Activated (electron-deficient) chloroarenes reacted also well at room temperature with 1 mol % Pd (Table 2, entries 1 and 2), while deactivated (electron-rich) substrates gave the desired coupling products in up to 99% yield at higher temperatures (Table 2, entries 4, 7–9). In addition to secondary amines also more challenging primary aliphatic amines such as *n*-butylamine can be coupled efficiently with aryl chlorides (entry 8). More interestingly this new catalyst system also works well with sensitive functionalized substrates. For example, 2-(*m*-chlorophenyl)ethanol can be coupled smoothly with anilines at low temperature (65 °C; Table 2, entry 9). Furthermore heteroaryl chlorides gave excellent yields with *N*-methylaniline (Table 2, entry 3), and the hindered *N*-cyclohexylaniline could be coupled with chlorobenzene in good yield (Table 2, entry 6).

Suzuki Coupling Reactions

In case of Suzuki reactions the behavior of the different ligands was studied more closely using the model reaction of a non-activated aryl chloride (*p*-chlorotoluene with phenylboronic acid). Initially the metal/ligand ratio was optimized at a low catalyst loading of 0.01 mol %

Table 2. Palladium-catalyzed amination of various aryl chlorides.

Entry	Aryl chloride	Amine	Product	Ligand	T [°C]	Yield [%][a]
1[b]				**4**	25	98
2[b]				**2**	25	86
3				**2**	80	98
4				**4**	80	99
5				**2**	80	99
6[c]				**4**	110	68
7				**2**	80	99
8				**2**	80	99
9[d]				**4**	65	60

Reaction conditions: 5 mmol aryl chloride, 6 mmol amine, 6 mmol NaO-*t*-Bu, 0.5 mol % $Pd(OA)_2$, 1 mol % ligand, 5 mL toluene, 20 h. Reaction time has not been minimized.

[a] Average of 2 runs, determined by GC using diethylene glycol di-*n*-butyl ether or hexadecane as internal standard.

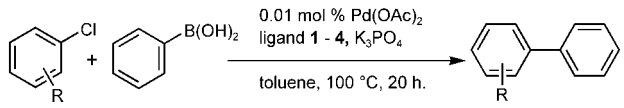
[b] 1 mol % $Pd(OAc)_2$, 2 mol % ligand.

[c] 5 mmol amine, 6 mmol aryl chloride, 7.5 mmol NaO-*t*-Bu, 9 mL toluene.

[d] 2 mmol aryl chloride, 2.4 mmol amine, 2.4 mmol NaO-*t*-Bu, 3 mL toluene.

$Pd(OAc)_2$ using ligand **3** in toluene. As shown in Table 3 in the presence of 0.1 mol % ligand (palladium/ligand ratio = 1/10) 4-methylbiphenyl is obtained in 86% yield (Table 3, entry 2). A lower ligand concentration as well as a higher one leads to significantly reduced yields of 4-methylbiphenyl (entries 1 and 3). Ligands **1**, **2**, and **4** were also tested, but ligand **3** was the only one that gave reproducible results at low catalyst concentration. It is not clear at this moment, which factors are decisive for the ligand's performance.

In further experiments ligands **3** and **4** were tested in the arylation of different aryl and heteroaryl chlorides (Table 4). The corresponding biaryls were obtained in excellent yields at low catalyst concentrations (0.01–0.05 mol % Pd) in most cases. *meta*- and *para*-substituted chloroarenes are easily coupled regardless of their



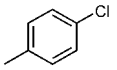
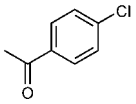
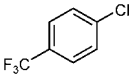
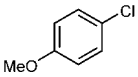
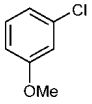
Scheme 3. Suzuki coupling of aryl chlorides.

Table 3. Suzuki reaction of *p*-chlorotoluene and phenylboronic acid.

Entry	Ligand	Pd:L	Yield [%][a]
1	**3**	1:2	57
2	**3**	1:10	86
3	**3**	1:20	79
4	**2**	1:10	50–83
5	**1**	1:10	15–66
6	**4**	1:10	59–95

Reaction conditions: 3 mmol *p*-chlorotoluene, 4.5 mmol phenylboronic acid, 6 mmol K_3PO_4, 0.01 mol % $Pd(OAc)_2$, 6 mL toluene, 100 °C, 20 h.
[a] Determined by GC using hexadecane as internal standard.

Table 4. Suzuki coupling of various aryl chlorides with phenylboronic acid.

Entry	Aryl chloride	Ligand	Catalyst [mol %]	Yield [%][a]	TON
1		**4**	0.05	95	1900
2		**3**	0.01	85	8500
3		**4**	0.05	93	1860
4		**3**	0.05	94	1880
5		**3**	0.05	84	1680
6		**3**	0.05	90	1800
7		**4**	0.05	44	880
8		**4**	0.05	99	1980

Reaction conditions: 3 mmol aryl chloride, 4.5 mmol phenylboronic acid, 6 mmol K_3PO_4, Pd:L = 1:10, 6 mL toluene, 100 °C, 20 h.
[a] Determined by GC using hexadecane as internal standard.

electronic nature (Table 4, entries 1–5). When 0.05 mol % Pd are applied, both ligands tested show highly reproducible results. In this case yields are almost the same for ligands **3** and **4**. However, the coupling of the sterically congested 2,6-dimethylchlorobenzene is more problematic, and a different performance of both ligands is observed. Here, 2,6-dimethylbiphenyl is obtained in moderate yield (44%) using ligand **4** (Table 4, entry 7). Surprisingly, the slightly slimmer ligand **3** performs even worse in this case (< 20% yield). However, the less bulky 2-chlorotoluene can be coupled efficiently in the presence of both ligands (90%; Table 4, entry 6). In addition, 3-chloropyridine provides an excellent 99% of the desired product (Table 4, entry 8).

Conclusions

Monodentate *N*-aryl-2-(dialkylphosphino)imidazoles and -benzimidazoles are conveniently synthesized by selective metallation at the 2-position of the respective heterocycle and quenching with chlorophosphines. This one-pot procedure should be applicable to a wide variety of similar ligands, enabling an easy preparation of a novel class of attractive ligands for aryl-X functionalization reactions. The prepared ligands have been shown to give good to very good performance in Suzuki reactions and Buchwald–Hartwig aminations of aryl and heteroaryl chlorides.

Experimental Section

General Remarks

All reactions were carried out under an argon atmosphere in dry Schlenk flasks. All solvents were made anhydrous by standard procedures. Ligands were synthesized and stored under an inert atmosphere using Schlenk techniques. Nevertheless, they can be handled in air for short periods without problems. All starting materials and reactants were used as received from commercial suppliers, except TMEDA which was distilled and degassed before use. NMR spectra were recorded on an ARX 400 (Bruker) spectrometer, chemical shifts were referred to undeuterated solvent, H_3PO_4 (80% in water) and $CFCl_3$ for ^1H, ^{13}C, ^{31}P and ^{19}F NMR, respectively. IR spectra were recorded on a Magna-IR-serie 550 (Nicolet) spectrometer. Mass spectra were recorded on an AMD 402 double focusing magnetic sector spectrometer (AMD Intectra). GC/MS spectra were recorded on an HP 5989A (Hewlett Packard) chromatograph equipped with a quadrupole analyzer. Gas chromatographic analyses were carried out on an HP 6890 (Hewlett Packard) chromatograph using an HP 5 column.

1-Phenyl-1*H*-benzimidazole

In a 100-mL Schlenk flask CuI (644 mg, 10 mol %), 1,10-phenanthroline (1.22 g, 20 mol %), benzimidazole (4.78 g,

40 mmol), and Cs_2CO_3 (19.3 g, 59.2 mmol) were evacuated twice and back-filled with argon. Iodobenzene (6.87 g, 33.7 mmol) and DMF (35 mL) were added. The Schlenk flask was sealed and the reaction mixture was stirred at 110 °C. After 24 h the suspension was cooled to room temperature, diluted with ethyl acetate and filtered through a plug of silica gel, eluting with ethyl acetate. The solution was concentrated and the resulting residue was purified by column chromatography (acetone/*n*-hexane) to provide the desired product as a colorless oil; yield: 5.2 g (79%). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.92 (s 1H), 7.72 (m, 1H), 7.40–7.33 (m, 3H), 7.28 (m, 3H), 7.15 (m, 2H); ^{13}C NMR (101 MHz, $CDCl_3$): δ = 144.0, 142.2, 136.2, 133.6, 129.9, 127.9, 123.9, 123.6, 122.7, 120.5, 110.4.

1-(1-Naphthyl)-1*H*-benzimidazole

In a 100-mL Schlenk flask CuI (374 mg, 10 mol %), 1,10-phenanthroline (708 mg, 20 mol %), benzimidazole (2.79 g, 23.6 mmol), and Cs_2CO_3 (13.4 g, 41.2 mmol) were evacuated twice and back-filled with argon. 1-Iodonaphthalene (5.0 g, 19.7 mmol) and DMF (20 mL) were added. The Schlenk flask was sealed and the reaction mixture was stirred at 145 °C. After 48 h the suspension was cooled to room temperature, diluted with ethyl acetate and filtered through a plug of silica gel, eluting with ethyl acetate. The solution was concentrated and the resulting residue was purified by column chromatography (acetone/*n*-hexane) to provide the desired product as a colorless oil; yield: 3.67 g (76%). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.04 (s, 1H), 7.90 (m, 3H), 7.48 (m, 3H), 7.29 (m, 3H), 7.14 (m, 1H), 6.99 (m, 1H); ^{13}C NMR (101 MHz, $CDCl_3$): δ = 143.7, 143.3, 135.6, 134.4, 132.3, 129.7, 129.6, 128.4, 127.5, 127.0, 125.4, 124.9, 123.5, 122.6, 122.5, 120.4, 110.8; IR (Cap/KBr): ν = 3054, 1716, 1597, 1488, 1405, 1286, 1144, 1006, 943, 770, 632, 475 cm^{-1}; MS (EI, 70 eV): *m/z* = 244 (100), 216 (10), 127 (9), 115 (6), 77 (4); HRMS: calcd. for $C_{17}H_{12}N_2$: 244.10005; found: 244.09980.

2-(Dicyclohexylphosphino)-*N*-mesitylimidazole (1)

In a 250-mL Schlenk flask *N*-mesitylimidazole (1.86 g, 10 mmol) was suspended in *n*-hexane (50 mL). TMEDA (1.6 mL, 10.6 mmol) and a solution of *n*-BuLi (1.6 M in *n*-hexane, 6.25 mL, 10 mmol) were added at room temperature, and the reaction mixture was refluxed for 2.5 h to get a yellow suspension. A solution of chlorodicyclohexylphosphine (10 mmol in 10 mL *n*-hexane) was added slowly *via* addition funnel. The mixture was further refluxed for 1 h. After cooling to room temperature, 30 mL degassed water were added. The aqueous layer was extracted with *n*-hexane (2 × 10 mL) and the combined organic layers were washed with degassed water (15 mL). The solution was dried over Na_2SO_4 and concentrated at room temperature to get a yellow viscous residue which was recrystallized from *n*-pentane to afford a white solid in two crops; yield: 2.2 g (58%). ^{1}H NMR (400 MHz, C_6D_6): δ = 7.45 (d, 1H, *J* = 1.0 Hz), 6.71 (s, 2H), 6.58 (dd, 1H, *J* = 1.0, 2.2 Hz), 2.4–1.0 (m, 31H); ^{13}C NMR (101 MHz, C_6D_6): δ = 147.5 (d, *J* = 16.2 Hz), 138.2, 135.3, 134.9, 131.4, 129.1, 122.6, 34.5 (d, *J* = 9.5 Hz), 30.8 (d, *J* = 10.5 Hz), 30.3 (d, *J* = 14.3 Hz), 27.6 (d, *J* = 7.6 Hz), 27.5 (d, *J* = 9.5 Hz), 26.8, 20.9, 18.4 (d, *J* = 4.8 Hz); ^{31}P NMR (162 MHz, C_6D_6): δ = −19.1; IR (KBr): ν = 3091, 2926, 2848, 1609, 1445, 1280, 1087, 1030, 854, 750, 489 cm^{-1}; MS (EI, 70 eV): *m/z* = 382 (11), 299 (100), 217 (24), 202 (7), 185 (27), 83 (7), 55 (21), 41 (9); HRMS (CI): calcd. for $C_{24}H_{36}N_2P$: 383.26161; found: 383.25907.

2-(Di-*tert*-butylphosphino)-*N*-mesitylimidazole (2)

In a 250-mL Schlenk flask *N*-mesitylimidazole (1.86 g, 10 mmol) was suspended in *n*-hexane (50 mL). TMEDA (1.6 mL, 10.6 mmol) and a solution of *n*-BuLi (1.6 M in *n*-hexane, 6.25 mL, 10 mmol) were added at room temperature, and the reaction mixture was refluxed for 2.5 h to get a yellow suspension. A solution of chlorodi-*tert*-butylphosphine (10 mmol in 10 mL *n*-hexane) was added slowly *via* addition funnel. The mixture was further refluxed for 1 h. After cooling to room temperature, 30 mL degassed water were added. The aqueous layer was extracted with *n*-hexane (2 × 10 mL) and the combined organic layers were washed with degassed water (15 mL). The solution was dried over Na_2SO_4 and concentrated at room temperature to furnish a yellow viscous liquid; yield: 2.95 g (80%). ^{1}H NMR (400 MHz, C_6D_6): δ = 7.42 (d, 1H, *J* = 1.0 Hz), 6.69 (s, 2H), 6.57 (dd, 1H, *J* = 1.0, 2.5 Hz), 2.08 (s, 3H), 1.96 (s, 6H), 1.30 (d, 18H, *J* = 12.1 Hz); ^{13}C NMR (101 MHz, C_6D_6): δ = 147.6 (d, *J* = 23.8 Hz), 138.5, 135.3, 134.6, 130.3, 129.2, 123.5, 33.7 (d, *J* = 16.2 Hz), 30.7 (d, *J* = 14.3 Hz), 21.2, 19.2 (d, *J* = 3.8 Hz); ^{31}P NMR (162 MHz, C_6D_6): δ = 11.9; IR (KBr): ν = 3101, 2982, 2952, 2861, 1610, 1592, 1473, 1280, 1178, 1104, 852, 750, 509 cm^{-1}; MS (EI, 70 eV): *m/z* = 330 (44), 274 (35), 218 (100), 185 (70), 158 (20), 91 (11), 57 (81), 41 (38); HRMS: calcd. for $C_{20}H_{31}N_2P$: 330.22247; found: 330.21794.

2-(Di-*tert*-butylphosphino)-*N*-phenyl-1*H*-benzimidazole (3)

In a 250-mL Schlenk flask *N*-phenyl-1*H*-benzimidazole (1.7 g, 8.76 mmol) was dissolved in 30 mL THF and TMEDA (1.4 mL, 9.27 mmol) was added. The solution was cooled to −65 °C and a solution of *n*-BuLi (1.6 M in *n*-hexane, 5.47 mL, 8.76 mmol) was added dropwise *via* addition funnel. The mixture was stirred for 1 h at −65 °C. A solution of chlorodi-*tert*-butylphosphine (8.76 mmol in 10 mL THF) was added slowly *via* addition funnel and the mixture was stirred for further 15 minutes at −65 °C and then at room temperature for 18 h. The solvents were removed at room temperature and the brown oily residue was dissolved in 30 mL CH_2Cl_2 and extracted with degassed water (2 × 20 mL). The aqueous layer was extracted with 10 mL CH_2Cl_2 and the combined organic layers were dried over Na_2SO_4 and concentrated at room temperature to furnish a brown viscous residue which was recrystallized from methanol; yield: 1.2 g (41%). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.80 (d, 1H, *J* = 8.1 Hz), 7.40 (m, 3H), 7.20 (m, 3H), 7.15 (m, 1H), 7.00 (m, 1H), 1.17 (d, 18H, *J* = 12.5 Hz); ^{13}C NMR (101 MHz, $CDCl_3$): δ = 155.0 (d, *J* = 26.7 Hz), 143.9, 137.2, 136.9, 129.2, 129.0 (d, *J* = 2.9 Hz), 128.6, 123.1, 122.3, 120.2, 110.7, 33.7 (d, *J* = 18.1 Hz), 30.2 (d, *J* = 14.3 Hz); ^{31}P NMR (162 MHz, $CDCl_3$): δ = 9.15; IR (KBr): ν = 3048, 2958, 2857, 1593, 1496, 1365, 1267, 1207, 1007, 826, 748, 699, 576 cm^{-1}; MS (EI, 70 eV): *m/z* = 338 (36), 282 (100), 267 (19), 225 (79), 147 (13),

107 (6), 77 (11), 57 (20), 41 (30); HRMS: calcd. for $C_{21}H_{27}N_2P$: 338.19119; found: 338.19061.

2-(Di-*tert*-butylphosphino)-*N*-(1-naphthyl)-1*H*-benzimidazole (4)

In a 250-ml Schlenk flask *N*-(1-naphthyl)-1*H*-benzimidazole (1.9 g, 7.86 mmol) was dissolved in 30 mL THF and TMEDA (1.25 mL, 8.26 mmol) was added. The solution was cooled to $-65\,^{\circ}C$ and a solution of *n*-BuLi (1.6 M in *n*-hexane, 4.91 mL, 7.86 mmol) was added dropwise *via* addition funnel. The mixture was stirred for 1 h at $-65\,^{\circ}C$. A solution of chloro-di-*tert*-butylphosphine (7.86 mmol in 15 mL THF) was added slowly *via* addition funnel and the mixture was stirred for further 15 minutes at $-65\,^{\circ}C$ and then at room temperature for 18 h. The solvents were removed at room temperature and the brown oily residue was dissolved in 30 mL CH_2Cl_2 and extracted with degassed water (2×20 mL). The aqueous layer was extracted with 10 mL CH_2Cl_2 and the combined organic layers were dried over Na_2SO_4 and concentrated at room temperature to afford a brown viscous residue which was recrystallized from methanol; yield: 1.0 g (33%). ^1H NMR (400 MHz, $CDCl_3$): $\delta = 7.99$ (m, 3H), 7.60 (m, 1H), 7.49 (m, 2H), 7.3 (m, 2H), 7.11 (m, 2H), 6.78 (m, 1H), 1.31 (d, 9H, $J = 12.2$ Hz), 1.17 (d, 9H, $J = 12.5$ Hz); ^{13}C NMR (101 MHz, $CDCl_3$): $\delta =$ 156.4 (d, $J = 27.6$ Hz), 143.8, 137.5, 134.2, 133.5 (d, $J =$ 1.9 Hz), 130.6, 129.6, 128.3, 127.8 (d, $J = 2.9$ Hz), 126.7, 126.5, 125.1, 123.5, 123.2, 122.2, 120.2, 111.0, 33.8 (d, $J = 18.1$ Hz), 32.0 (d, $J = 18.1$ Hz), 30.4 (d, $J = 14.3$ Hz), 30.4 (d, $J =$ 14.3 Hz); ^{31}P NMR (162 MHz, $CDCl_3$): $\delta = 10.43$; IR (KBr): $\nu = 3051$, 2965, 2861, 1596, 1469, 1414, 1177, 947, 826, 772, 743, 515 cm^{-1}; MS (EI, 70 eV): 388 (33), 332 (49), 317 (25), 276 (100), 147 (8), 57 (26), 41 (18); HRMS: calcd. for $C_{25}H_{29}N_2P$: 388.20685; found: 388.20694.

Buchwald–Hartwig Amination

A 30-mL pressure tube was loaded with $Pd(OAc)_2$ (5.6 mg, 0.025 mmol), the ligand (0.050 mmol), and NaO-*t*-Bu (577 mg, 6.0 mmol) and purged with argon. Then, toluene (5 mL), the aryl chloride (5 mmol), and the amine (6 mmol) were added successively. The mixture was stirred for the mentioned time and temperature. After cooling to room temperature the mixture was diluted with diethyl ether (5 mL) and washed with water (10 mL). The organic phase was dried over $MgSO_4$, concentrated under vacuum and the product was isolated by column chromatography (silica, ethyl acetate/*n*-hexane or acetone/*n*-hexane). Alternatively, diethylene glycol di-*n*-butyl ether or hexadecane was added as internal standard and quantitative analysis was done by gas chromatography. The commercially available products were identified by comparison of their GC/MS data with the data of authentic samples, known products were identified by NMR and mass spectroscopy.

Suzuki Reaction

A 30-mL pressure tube was loaded with $Pd(OAc)_2$, the ligand, K_3PO_4 (6 mmol), and phenylboronic acid (4.5 mmol) and was purged with argon. Then, toluene (6 mL) and the aryl chloride (3 mmol) were added. The mixture was stirred for 20 h at $100\,^{\circ}C$. After cooling to room temperature the mixture was diluted with diethyl ether (10 mL) and washed with aqueous sodium hydroxide (1 M, 10 mL). The organic phase was dried over Na_2SO_4, concentrated under vacuum and the product was isolated by column chromatography (silica, ethyl acetate/*n*-hexane). Alternatively, hexadecane was added as internal standard and quantitative analysis was done by gas chromatography. The commercially available products were identified by comparison of their GC/MS data with the data of authentic samples, known products were identified by NMR and mass spectroscopy.

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